String Theory, at 20, Explains It All (or Not)

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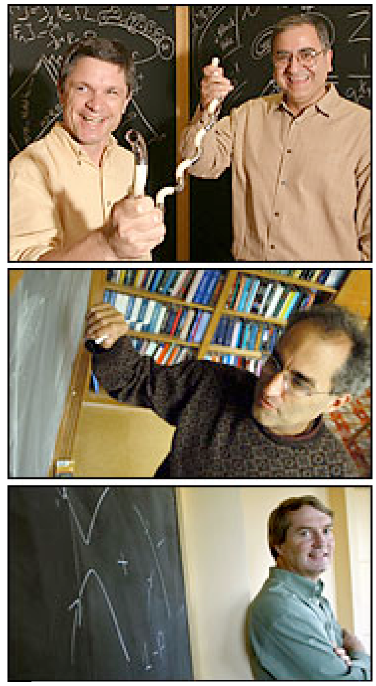

From top, Rick Friedman; Laura Pedrick; Emilio Flores, all for The New York Times

Scientists around the country leading the study of string theory include Dr. Andrew Strominger and Dr. Cumrun Vafa, photo at top; Dr. Edward Witten, middle; and Dr. Joe Polchinski, above.

ASPEN, Colo. - They all laughed 20 years ago.

It was then that a physicist named John Schwarz jumped up on the stage during a cabaret at the physics center here and began babbling about having discovered a theory that could explain everything. By prearrangement men in white suits swooped in and carried away Dr. Schwarz, then a little-known researcher at the California Institute of Technology.

Only a few of the laughing audience members knew that Dr. Schwarz was not entirely joking. He and his collaborator, Dr. Michael Green, now at Cambridge University, had just finished a calculation that would change the way physics was done. They had shown that it was possible for the first time to write down a single equation that could explain all the laws of physics, all the forces of nature - the proverbial "theory of everything" that could be written on a T-shirt.

And so emerged into the limelight a strange new concept of nature, called string theory, so named because it depicts the basic constituents of the universe as tiny wriggling strings, not point particles.

"That was our first public announcement," Dr. Schwarz said recently.

By uniting all the forces, string theory had the potential of achieving the goal that Einstein sought without success for half his life and that has embodied the dreams of every physicist since then. If true, it could be used like a searchlight to illuminate some of the deepest mysteries physicists can imagine, like the origin of space and time in the Big Bang and the putative death of space and time at the infinitely dense centers of black holes.

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Slide Show: 20 Years of String Theory

In the last 20 years, string theory has become a major branch of physics. Physicists and mathematicians conversant in strings are courted and recruited like star quarterbacks by universities eager to establish their research credentials. String theory has been celebrated and explained in best-selling books like "The Elegant Universe," by Dr. Brian Greene, a physicist at Columbia University, and even on popular television shows.

Last summer in Aspen, Dr. Schwarz and Dr. Green (of Cambridge) cut a cake decorated with "20th Anniversary of the First Revolution Started in Aspen," as they and other theorists celebrated the anniversary of their big breakthrough. But even as they ate cake and drank wine, the string theorists admitted that after 20 years, they still did not know how to test string theory, or even what it meant.

As a result, the goal of explaining all the features of the modern world is as far away as ever, they say. And some physicists outside the string theory camp are growing restive. At another meeting, at the Aspen Institute for Humanities, only a few days before the string commemoration, Dr. Lawrence Krauss, a cosmologist at Case Western Reserve University in Cleveland, called string theory "a colossal failure."

String theorists agree that it has been a long, strange trip, but they still have faith that they will complete the journey.

"Twenty years ago no one would have correctly predicted how string theory has since developed," said Dr. Andrew Strominger of Harvard. "There is disappointment that despite all our efforts, experimental verification or disproof still seems far away. On the other hand, the depth and beauty of the subject, and the way it has reached out, influenced and connected other areas of physics and mathematics, is beyond the wildest imaginations of 20 years ago."

In a way, the story of string theory and of the physicists who have followed its siren song for two decades is like a novel that begins with the classic "what if?"

What if the basic constituents of nature and matter were not little points, as had been presumed since the time of the Greeks? What if the seeds of reality were rather teeny tiny wiggly little bits of string? And what appear to be different particles like electrons and quarks merely correspond to different ways for the strings to vibrate, different notes on God's guitar?

It sounds simple, but that small change led physicists into a mathematical labyrinth, in which they describe themselves as wandering, "exploring almost like experimentalists," in the words of Dr. David Gross of the Kavli Institute for Theoretical Physics in Santa Barbara, Calif.

String theory, the Italian physicist Dr. Daniele Amati once said, was a piece of 21st-century physics that had fallen by accident into the 20th century.

And, so the joke went, would require 22nd-century mathematics to solve.

Dr. Edward Witten of the Institute for Advanced Study in Princeton, N.J., described it this way: "String theory is not like anything else ever discovered. It is an incredible panoply of ideas about math and physics, so vast, so rich you could say almost anything about it."

The string revolution had its roots in a quixotic effort in the 1970's to understand the so-called "strong" force that binds quarks into particles like protons and neutrons. Why were individual quarks never seen in nature? Perhaps because they were on the ends of strings, said physicists, following up on work by Dr. Gabriele Veneziano of CERN, the European research consortium.

That would explain why you cannot have a single quark - you cannot have a string with only one end. Strings seduced many physicists with their mathematical elegance, but they had some problems, like requiring 26 dimensions and a plethora of mysterious particles that did not seem to have anything to do with quarks or the strong force.

When accelerator experiments supported an alternative theory of quark behavior known as quantum chromodynamics, most physicists consigned strings to the dustbin of history.

But some theorists thought the mathematics of strings was too beautiful to die.

In 1974 Dr. Schwarz and Dr. Joel Scherk from the École Normale Supérieure in France noticed that one of the mysterious particles predicted by string theory had the properties predicted for the graviton, the particle that would be responsible for transmitting gravity in a quantum theory of gravity, if such a theory existed.

Without even trying, they realized, string theory had crossed the biggest gulf in physics. Physicists had been stuck for decades trying to reconcile the quirky rules known as quantum mechanics, which govern atomic behavior, with Einstein's general theory of relativity, which describes how gravity shapes the cosmos.

That meant that if string theory was right, it was not just a theory of the strong force; it was a theory of all forces.

"I was immediately convinced this was worth devoting my life to," Dr. Schwarz recalled "It's been my life work ever since."

It was another 10 years before Dr. Schwarz and Dr. Green (Dr. Scherk died in 1980) finally hit pay dirt. They showed that it was possible to write down a string theory of everything that was not only mathematically consistent but also free of certain absurdities, like the violation of cause and effect, that had plagued earlier quantum gravity calculations.

In the summer and fall of 1984, as word of the achievement spread, physicists around the world left what they were doing and stormed their blackboards, visions of the Einsteinian grail of a unified theory dancing in their heads.

"Although much work remains to be done there seem to be no insuperable obstacles to deriving all of known physics," one set of physicists, known as the Princeton string quartet, wrote about a particularly promising model known as heterotic strings. (The quartet consisted of Dr. Gross; Dr. Jeffrey Harvey and Dr. Emil Martinec, both at the University of Chicago; and Dr. Ryan M. Rohm, now at the University of North Carolina.)

The Music of Strings

String theory is certainly one of the most musical explanations ever offered for nature, but it is not for the untrained ear. For one thing, the modern version of the theory decreed that there are 10 dimensions of space and time.

To explain to ordinary mortals why the world appears to have only four dimensions - one of time and three of space -string theorists adopted a notion first bruited by the German mathematicians Theodor Kaluza and Oskar Klein in 1926. The extra six dimensions, they said, go around in sub-submicroscopic loops, so tiny that people cannot see them or store old National Geographics in them.

A simple example, the story goes, is a garden hose. Seen from afar, it is a simple line across the grass, but up close it has a circular cross section. An ant on the hose can go around it as well as travel along its length. To envision the world as seen by string theory, one only has to imagine a tiny, tiny six-dimensional ball at every point in space-time

But that was only the beginning. In 1995, Dr. Witten showed that what had been five different versions of string theory seemed to be related. He argued that they were all different manifestations of a shadowy, as-yet-undefined entity he called "M theory," with "M" standing for mother, matrix, magic, mystery, membrane or even murky.

In M-theory, the universe has 11 dimensions - 10 of space and one of time, and it consists not just of strings but also of more extended membranes of various dimension, known generically as "branes."

This new theory has liberated the imaginations of cosmologists. Our own universe, some theorists suggest, may be a four-dimensional brane floating in some higher-dimensional space, like a bubble in a fish tank, perhaps with other branes - parallel universes - nearby. Collisions or other interactions between the branes might have touched off the Big Bang that started our own cosmic clock ticking or could produce the dark energy that now seems to be accelerating the expansion of the universe, they say.

Toting Up the Scorecard

One of string theory's biggest triumphs has come in the study of black holes. In Einstein's general relativity, these objects are bottomless pits in space-time, voraciously swallowing everything, even light, that gets too close, but in string theory they are a dense tangle of strings and membranes.

In a prodigious calculation in 1995, Dr. Strominger and Dr. Cumrun Vafa, both of Harvard, were able to calculate the information content of a black hole, matching a famous result obtained by Dr. Stephen Hawking of Cambridge University using more indirect means in 1973. Their calculation is viewed by many people as the most important result yet in string theory, Dr. Greene said.

Another success, Dr. Greene and others said, was the discovery that the shape, or topology, of space, is not fixed but can change, according to string theory. Space can even rip and tear.

But the scorecard is mixed when it comes to other areas of physics. So far, for example, string theory has had little to say about what might have happened at the instant of the Big Bang..

Moreover, the theory seems to have too many solutions. One of the biggest dreams that physicists had for the so-called theory of everything was that it would specify a unique prescription of nature, one in which God had no choice, as Einstein once put it, about details like the number of dimensions or the relative masses of elementary particles.

But recently theorists have estimated that there could be at least 10^{100} different solutions to the string equations, corresponding to different ways of folding up the extra dimensions and filling them with fields - gazillions of different possible universes.

Some theorists, including Dr. Witten, hold fast to the Einsteinian dream, hoping that a unique answer to the string equations will emerge when they finally figure out what all this 21st-century physics is trying to tell them about the world.

But that day is still far away.

"We don't know what the deep principle in string theory is," Dr. Witten said.

For most of the 20th century, progress in particle physics was driven by the search for symmetries - patterns or relationships that remain the same when we swap left for right, travel across the galaxy or imagine running time in reverse.

For years physicists have looked for the origins of string theory in some sort of deep and esoteric symmetry, but string theory has turned out to be weirder than that.

Recently it has painted a picture of nature as a kind of hologram. In the holographic images often seen on bank cards, the illusion of three dimensions is created on a two-dimensional surface. Likewise string theory suggests that in nature all the information about what is happening inside some volume of space is somehow encoded on its outer boundary, according to work by several theorists, including Dr. Juan Maldacena of the Institute for Advanced Study and Dr. Raphael Bousso of the University of California, Berkeley.

Just how and why a three-dimensional reality can spring from just two dimensions, or four dimensions can unfold from three, is as baffling to people like Dr. Witten as it probably is to someone reading about it in a newspaper.

In effect, as Dr. Witten put it, an extra dimension of space can mysteriously appear out of "nothing."

The lesson, he said, may be that time and space are only illusions or approximations, emerging somehow from something more primitive and fundamental about nature, the way protons and neutrons are built of quarks.

The real secret of string theory, he said, will probably not be new symmetries, but rather a novel prescription for constructing space-time.

"It's a new aspect of the theory," Dr. Witten said. "Whether we are getting closer to the deep principle, I don't know."

As he put it in a talk in October, "It's plausible that we will someday understand string theory."

Tangled in Strings

Critics of string theory, meanwhile, have been keeping their own scorecard. The most glaring omission is the lack of any experimental evidence for strings or even a single experimental prediction that could prove string theory wrong - the acid test of the scientific process.

Strings are generally presumed to be so small that "stringy" effects should show up only when particles are smashed together at prohibitive energies, roughly 10^{19} billion electron volts. That is orders of magnitude beyond the capability of any particle accelerator that will ever be built on earth. Dr. Harvey of Chicago said he sometimes woke up thinking, What am I doing spending my whole career on something that can't be tested experimentally?

This disparity between theoretical speculation and testable reality has led some critics to suggest that string theory is as much philosophy as science, and that it has diverted the attention and energy of a generation of physicists from other perhaps more worthy pursuits. Others say the theory itself is still too vague and that some promising ideas have not been proved rigorously enough yet.

Dr. Krauss said, "We bemoan the fact that Einstein spent the last 30 years of his life on a fruitless quest, but we think it's fine if a thousand theorists spend 30 years of their prime on the same quest."

The Other Quantum Gravity

String theory's biggest triumph is still its first one, unifying Einstein's lordly gravity that curves the cosmos and the quantum pinball game of chance that lives inside it.

"Whatever else it is or is not," Dr. Harvey said in Aspen, "string theory is a theory of quantum gravity that gives sensible answers."

That is no small success, but it may not be unique.

String theory has a host of lesser known rivals for the mantle of quantum gravity, in particular a concept called, loop quantum gravity, which arose from work by Dr. Abhay Ashtekar of Penn State and has been carried forward by Dr. Carlo Rovelli of the University of Marseille and Dr. Lee Smolin of the Perimeter Institute for Theoretical Physics in Waterloo, Ontario, among others.

Unlike string theory, loop gravity makes no pretensions toward being a theory of everything. It is only a theory of gravity, space and time, arising from the applications of quantum principles to the equations of Einstein's general relativity. The adherents of string theory and of loop gravity have a kind of Microsoft-Apple kind of rivalry, with the former garnering a vast majority of university jobs and publicity.

Dr. Witten said that string theory had a tendency to absorb the ideas of its critics and rivals. This could happen with loop gravity. Dr. Vafa; his Harvard colleagues, Dr. Sergei Gukov and Dr. Andrew Neitzke; and Dr. Robbert Dijkgraaf of the University of Amsterdam report in a recent paper that they have found a connection between simplified versions of string and loop gravity.

"If it exists," Dr. Vafa said of loop gravity, "it should be part of string theory."

Looking for a Cosmic Connection

Some theorists have bent their energies recently toward investigating models in which strings could make an observable mark on the sky or in experiments in particle accelerators.

"They all require us to be lucky," said Dr. Joe Polchinski of the Kavli Institute.

For example the thrashing about of strings in the early moments of time could leave fine lumps in a haze of radio waves filling the sky and thought to be the remains of the Big Bang. These might be detectable by the Planck satellite being built by the European Space Agency for a 2007 launching date, said Dr. Greene.

According to some models, Dr. Polchinski has suggested, some strings could be stretched from their normal submicroscopic lengths to become as big as galaxies or more during a brief cosmic spurt known as inflation, thought to have happened a fraction of a second after the universe was born.

If everything works out, he said, there will be loops of string in the sky as big as galaxies. Other strings could stretch all the way across the observable universe. The strings, under enormous tension and moving near the speed of light, would wiggle and snap, rippling space-time like a tablecloth with gravitational waves.

"It would be like a whip hundreds of light-years long," Dr. Polchinski said.

The signal from these snapping strings, if they exist, should be detectable by the Laser Interferometer Gravitational Wave Observatory, which began science observations two years ago, operated by a multinational collaboration led by Caltech and the Massachusetts Institute of Technology.

Another chance for a clue will come in 2007 when the Large Hadron Collider is turned on at CERN in Geneva and starts colliding protons with seven trillion volts of energy apiece. In one version of the theory - admittedly a long shot - such collisions could create black holes or particles disappearing into the hidden dimensions.

Everybody's favorite candidate for what the collider will find is a phenomenon called supersymmetry, which is crucial to string theory. It posits the existence of a whole set of ghostlike elementary particles yet to be discovered. Theorists say they have reason to believe that the lightest of these particles, which have fanciful names like photinos, squarks and selectrons, should have a mass-energy within the range of the collider.

String theory naturally incorporates supersymmetry, but so do many other theories. Its discovery would not clinch the case for strings, but even Dr. Krauss of Case Western admits that the existence of supersymmetry would be a boon for string theory.

And what if supersymmetric particles are not discovered at the new collider? Their absence would strain the faith, a bit, but few theorists say they would give up.

"It would certainly be a big blow to our chances of understanding string theory in the near future," Dr. Witten said.

Beginnings and Endings

At the end of the Aspen celebration talk turned to the prospect of verification of string theory. Summing up the long march toward acceptance of the theory, Dr. Stephen Shenker, a pioneer string theorist at Stanford, quoted Winston Churchill:

"This is not the end, not even the beginning of the end, but perhaps it is the end of the beginning."

Dr. Shenker said it would be great to find out that string theory was right.

From the audience Dr. Greene piped up, "Wouldn't it be great either way?"

"Are you kidding me, Brian?" Dr. Shenker responded. "How many years have you sweated on this?"

But if string theory is wrong, Dr. Greene argued, wouldn't it be good to know so physics could move on? "Don't you want to know?" he asked.

Dr. Shenker amended his remarks. "It would be great to have an answer," he said, adding, "It would be even better if it's the right one."